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14. ABSTRACT During June 2008 broad plasma density decreases (BPDs) were detected repeatedly by the Planar Langmuir Probe (PLP) on board the Communications/Navigation Outage Forecasting System (C/NOFS) satellite. These density minima, not to be confused with Equatorial Plasma Bubbles (EPBs), occurred within 15° of the equator, consisted of reductions in plasma density up to an order of magnitude and extended across several degrees in azimuth along the orbit. Analysis revealed that the BPDs occurred nearly daily from May through July 2008 on C/NOFS, and that the widest BPDs were observed in the vicinity of the South Atlantic Anomaly (SAA). Similar BPDs simultaneous with the C/NOFS measurements were observed by instruments on the CHAllenging Minisatellite Payload (CHAMP) and Defense Meteorological Program (DMSP) satellites. An examination of plasma densities revealed that these phenomena were a frequent occurrence during (1) the period around June solstices; during (2) solar minimum years); (3) in the vicinity of the SAA. Neutral densities were examined during periods when BPDs were detected, and at times there are simultaneous neutral depletions. One possible explanation is a decrease in temperature of both ions and neutrals in the equatorial region at these times, consistent with downwelling in the ionosphere and thermosphere. Measurements of plasma temperatures on DMSP support this hypothesis.

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Broad plasma decreases in the equatorial ionosphere

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[1] During June 2008 broad plasma density decreases (BPDs) were detected repeatedly by the Planar Langmuir Probe (PLP) on board the Communication/Navigation Outage Forecasting System (C/NOFS) satellite. These density minima, not to be confused with Equatorial Plasma Bubbles (EPBs), occurred within 15° of the equator, consisted of reductions in plasma density up to an order of magnitude and extended across several degrees in azimuth along the orbit. Analysis revealed that the BPDs occurred nearly daily from May through July 2008 on C/NOFS, and that the widest BPDs were observed in the vicinity of the South Atlantic Anomaly (SAA). Similar BPDs simultaneous with the C/NOFS measurements were observed by instruments on the CHAllenging Minisatellite Payload (CHAMP) and Defense Meteorological Satellite Program (DMSP) satellites. An examination of plasma densities observed by the DMSP satellites over several years revealed that these phenomena were a frequent occurrence during (1) the period around June solstices; during (2) solar minimum years; (3) in the vicinity of the SAA. Neutral densities were examined during periods when BPDs were detected, and at times there are simultaneous neutral depletions. One possible explanation is a decrease in temperature of both ions and neutrals in the equatorial region at these times, consistent with downwelling in the ionosphere and thermosphere. Measurements of plasma temperatures on DMSP support this hypothesis. **Citation:** Huang, C. Y., F. A. Marcos, P. A. Roddy, M. R. Hairston, W. R. Coley, C. Roth, S. Bruinsma, and D. E. Hunton (2009), Broad plasma decreases in the equatorial ionosphere, *Geophys. Res. Lett.*, *36*, L00C04, doi:10.1029/2009GL039423.

1. Introduction

[2] Between May and August 2008, the Planar Langmuir Probe (PLP) on the C/NOFS satellite regularly measured reduced plasma density on the nightside in the equatorial region lasting several minutes and occurring over a broad range of longitudes. Density within the depleted region was reduced by up to an order of magnitude below the density outside the Broad Plasma Decrease (BPD). The June 2008 solstice occurred during an extremely quiet solar minimum interval. The minimum Disturbance Storm Time (Dst) index value during the month was −40 nT and this occurred on 15 June. There are several periods when the Auroral Electrojet (AE) index reaches 1000 nT, but these do not correlate with the nearly daily occurrences of BPDs.

[3] Densities on the DMSP satellites were examined for the same interval, and BPDs were noted at or near equatorial latitudes. The deepest BPDs were observed close to the SAA which encompasses the entire azimuthal area from the west coast of South America to the center of southern Africa and from the geographic equator to 50° S. Density depletions were observed on DMSP up to 40% below the ambient density outside the depleted area.

[4] We have studied these depletions using a large array of satellite-based observations of the ionosphere-thermosphere (IT) system in order to determine their climatology. This report briefly summarizes the results of our study of IT observations and our interpretation of these observations.

2. Instrumentation

[5] The PLP on C/NOFS measures plasma densities, electron temperatures and density fluctuations at rates ranging from 32 to 1024 samples per second. In this paper we focus on electron densities on the nightside. During the period in this study, 17–19 June 2008, the satellite altitude when depletions were observed varied from 400 to 600 km, with the bulk of measurements made between 400 and 500 km.

[6] Density measurements on DMSP were made by the Special Sensors-Ions, Electrons, and Scintillation (SSIES) suite. The measurements used in this study come from SSIES-3 flown on DMSP F16. We use output from the Retarding Potential Analyzer (RPA) which gives plasma densities and temperatures every 1 s, over the range 10^2–10^6 cm^{-3} with an accuracy of 10%.

[7] Plasma densities on the CHAMP satellite were obtained from the PLP [*Cooke et al.*, 2003; *Roth*, 2004], which monitors the spacecraft potential, ion density, and electron temperature. A one-second sweep is performed every 15 seconds. Neutral densities were measured by the STAR accelerometer [*Bruinsma et al.*, 2004] every 10 seconds.

[8] Neutral densities on the Gravity Recovery and Climate Experiment (GRACE) satellite were measured using super-STAR accelerometers, similar to the STAR accelerometer on CHAMP, [*Cheng et al.*, 2008] with a precision an order of magnitude greater than the CHAMP instrument. In this study, 5-second averaged data were used.

3. Observations

[9] An example of the observations which triggered this investigation is shown in Figure 1. In Figure 1a, shown is

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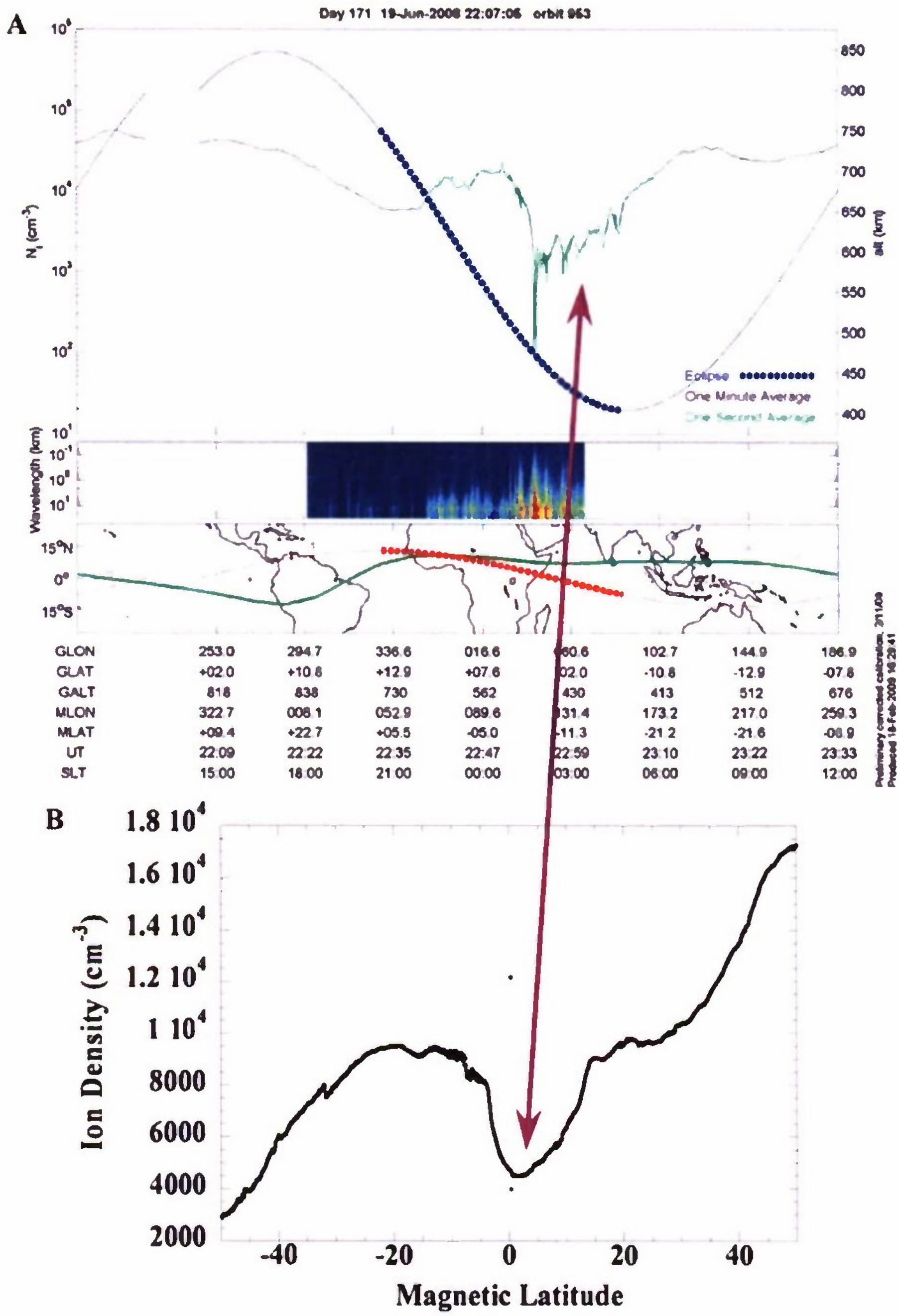

Figure 1. C/NOFS and DMSP observations of a Broad Plasma Depletion (BPD) on 19 June 2008. (a, top) Plasma density (black line) in 1-minute resolution, as well as 1-second resolution (green line). C/NOFS altitude is indicated by the blue line, with the heavy dotted section showing when the satellite is in darkness. (middle) Spectrum of the high-time resolution density fluctuations. (bottom) The magnetic equator is shown by a green trace, and satellite orbit is indicated by the red trace, with the heavy dotted section indicating when the spacecraft is in darkness. The BPD (purple arrow) starts at 2253 UT, with recovery after 2310 UT. (b) In the DMSP F16 plot the ion density is plotted as a function of magnetic latitude during an equatorial crossing at 2236 UT. The BPD (purple arrow) occurs at the equator as indicated.

the PLP plot from C/NOFS on 19 June 2008. In Figure 1a (top), plasma density is indicated by the black trace which shows 1-minute averaged data. 1-second data are illustrated by the green trace. Also shown is the satellite altitude in blue with the heavy dotted line indicating when the spacecraft is in darkness. In Figure 1a (middle), the color spectrogram shows the frequency of the density fluctuations. Figure 1a (bottom) shows the orbit of the satellite in red, the heavy dotted segment showing when C/NOFS is in darkness. The magnetic equator is plotted in green.

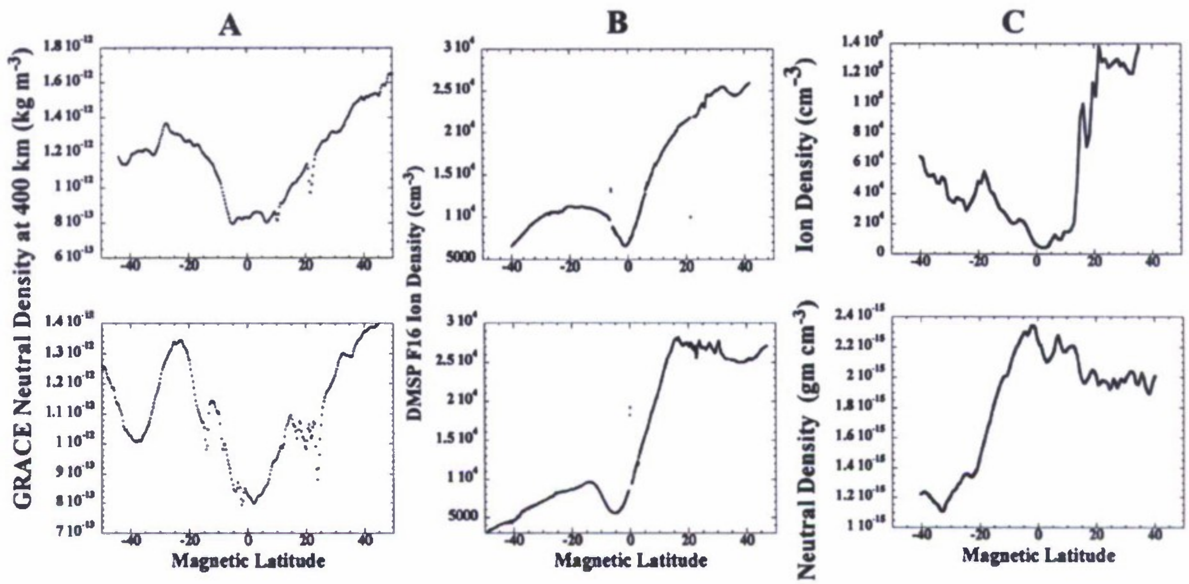

Figure 2. (a) Two consecutive nightside orbits of GRACE on 9 June 2005. (top) The first crossing occurred at 2200 UT, 20.3 MLT, 329°E. long. (geog.), altitude of 468 km; (bottom) the second at 2333 UT, 20.2 MLT, 305°E. long. (geog.), 470 km altitude. (b) DMSP F16 equatorial crossings on the same day. (top) The crossing at 2114 UT, 20.5 MLT, 343°E. long. (geog.); (bottom) the plasma density at 2253 UT, 20.6 MLT, 320°E. long. (geog.). Reduced neutral and plasma densities in all four plots can be clearly seen. (c) CHAMP ion and neutral densities at 2224 UT, 17 June 2008. Satellite location is 1.23 MLT, 329 km altitude, 40°E long. (geog.) (top) The plasma density is shown, as a function of latitude. (bottom) CHAMP Neutral density.

[10] At approximately 2253 UT, at an altitude of about 475 km, and at 40° E geog. long., the plasma density decreases sharply as illustrated by the black trace. Densities gradually recover, and are at their pre-depleted level by 2310 UT. The magnetic latitude of the plasma decrease varies from $-8°$ to $-21°$. In 1B, below, is shown the DMSP F16 plot of plasma densities for the equatorial crossing at 2236 UT. The orbit corresponds to a single crossing of the eveningside equatorial ionosphere at an altitude of 840 km, and magnetic local time (MLT) of 20.2. Note that while the C/NOFS and DMSP measurements are nearly simultaneous, there is considerable spatial separation between the two satellites. The magnetic equator is placed at the center of the plot, and latitudes from $-50°$ S to 50° N are shown in intervals of 10°. Indicated by the arrow, there is a large reduction in plasma density in the equator at 2236 UT, at 318° E geographic longitude (geog. long.), corresponding to the SAA.

[11] Accurate statistics for C/NOFS cannot be obtained due to the orbital variations in altitude, latitude and longitude during the May–July 2008 interval. However in this period, barring data gaps, on all but 8 days BPDs were observed by the PLP. On most days, BPDs were seen on multiple orbits if the satellite was in the vicinity of the SAA on the nightside.

[12] As can be seen in Figure 1, the extent of the depleted region is large. In the C/NOFS plot, the area exceeds 60° in longitude and 15° in latitude. The DMSP depletion is more than 15° in latitude. For this reason, we are careful to describe these as broad plasma density decreases (BPDs), not to be confused with EPBs which are orders of magnitude smaller in spatial extent. However there is a relation between BPDs and EPBs. BPDs generally originate over the SAA, and are relatively shallow and unstructured. Over subsequent orbits of C/NOFS, they migrate eastward, and the depletion becomes narrower and deeper. When the BPD reaches the dawn meridian, they are considerably narrower with very deep structures within the BPD. For more detail, we refer the reader to *de la Beaujardière et al.* [2009].

[13] Having confirmed the presence of BPDs on DMSP in June 2008, we examined its extensive database for other examples. We found that BPDs occur regularly on the nightside in (1) June solstices which occur (2) during solar minima, (3) predominantly in the SAA. During the period from 1 May–31 July 2008, BPDs were observed on DMSP F16 on 87 of the 92 days. In addition, during intervals centered on the June solstices of 1995, 1996, 2005, 2006 and 2007 we found BPDs on DMSP repeatedly.

[14] Neutral densities were also examined for possible connection with the BPDs. CHAMP and GRACE accelerometer data were studied for the periods when large BPDs were recorded. Examples of neutral density decreases observed on GRACE are shown in Figure 2a. On 9 June 2005, two successive nightside orbits are shown. In Figure 2a (top), the equatorial crossing occurred at 22 UT, at a location of 20.3 MLT, altitude of 468 km, 329° E geog. long. In Figure 2a (bottom), the equatorial crossing occurred at 2333 UT, at 20.2 MLT and 470 km altitude, 305°E geog. long. In both orbits, reductions in neutral density up to 45% can be seen around the equator. The other 12 equatorial

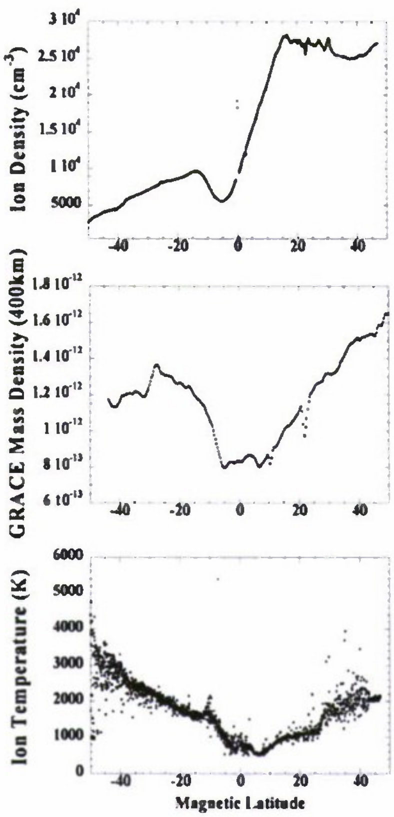

Figure 3. (top) Plasma density and (bottom) temperature from DMSP F16 on 9 June 2005, with (middle) GRACE neutral density. Plasma and neutral densities are both reduced in the equatorial region. Lower temperatures at the equator clearly indicate cooling at this time.

crossings on this day which do not occur close to the SAA do not display this phenomenon.

[15] In Figure 2b are shown two equatorial crossings made by DMSP F16 on the same day. Figure 2b (top) shows measurements made at 2114 UT, at a 343°E geog. long., and 20.5 MLT. Figure 2b (bottom) shows the subsequent crossing at 2253 UT, 320°E geog. long., and 20.6 MLT. These crossings are nearly coincident both in time and space with the GRACE equatorial orbits on the left side of Figure 2. The density reductions inside the BPDs on DMSP are approximately 40% of ambient values.

[16] On 17 June 2008, on three consecutive equatorial crossings between 2048 and 2400 UT, the PLP on CHAMP detected deep BPDs. The CHAMP orbit crossed C/NOFS at 2355 UT which observed highly structured BPDs at this time. During the 2224 UT crossing, second of the three, CHAMP was located at 329 km altitude, 1.23 MLT, 40°E geog. long. In Figure 2c are shown the ion and neutral densities during this crossing. The PLP densities show a BPD which is over 30° across in latitude, with a plasma density that is more than an order of magnitude below ambient values. The neutral density decrease is about 10% below the densities outside the neutral depletion. It is not clear whether the difference between this example and that shown in Figure 2a is due to the significantly lower neutral densities during 2008, or if this represents a difference in the phenomenology.

4. Discussion

[17] The appearance of BPDs can be explained in several ways. For a number of reasons we rule out the possibility of EPBs as the cause. The climatology of EPBs is in conflict with the climatology of the BPDs [*Gentile et al.*, 2006]. During solar minimum, there are few EPBs which reach DMSP altitude, and during June EPB occurrence in the SAA region is low [*Huang et al.*, 2002]. During times of maximum occurrence of EPBs during the December solstices and equinoxes, BPDs have not been detected. As already mentioned, the size of BPDs exceeds normal EPBs by a large factor.

[18] A second possible cause of BPDs and neutral depletions is a change in chemistry in the ionosphere and thermosphere. This occurs during magnetic storms, when large changes in IT densities occur [*Crowley et al.*, 2006]. Other systemic variations in the thermosphere occur as a result of global warming [*Akmaev et al.*, 2006]. However neither of these mechanisms can account for the specific climatology associated with the BPDs, nor the simultaneous decreases in neutral and ion densities in the equatorial region.

[19] Coincident reductions in neutral and plasma densities narrow the range of possible causes. Simultaneous ion and neutral density reductions have been observed in EPBs [*Bencze et al.*, 2000] but as we have pointed out, these BPDs cannot be bubbles. The minima in ion and neutral densities can be described by a change in the topside scale height, defined as H = kT/mg where k is Boltzmann's constant, T is the temperature of the species, m the mass of the species and g the gravitational constant [*Rishbeth and Garriott*, 1969].

[20] A change in plasma and neutral density can be due to a change in T, the plasma or neutral temperature, or m, the mass of the species, or both. An examination of the fraction of light ions (H^+) during the DMSP observations shows that during the June 2005 events, this fraction is less than 50% in the minimum of the BPD, and the opposite is true during June 2008, when the solar cycle is in a deep minimum. This rules out a persistent change in ion composition.

[21] We suggest that the most likely explanation is a cooling or downwelling of the equatorial region during these periods. This would account for simultaneous decreases in both neutrals and plasma density. To verify this hypothesis, we examined ion temperatures (T_i) on DMSP during the periods when BPDs were seen. In Figure 3 (bottom), we show T_i obtained from DMSP F16 during the 2253 UT equatorial crossing on 9 June 2005, together with ion density (Figure 3, top) measured simultaneously and the GRACE neutral density (Figure 3, middle) from the 2333 UT crossing. There is a clear decrease in T_i at the equator of approximately 50% to a minimum value of 547K. This is comparable in spatial extent with the BPD noted on DMSP and the neutral depletion on GRACE. Similar variations in T_i occur during the 2114 UT crossing.

[22] During 2008 the plasma density in the BPD is reduced to such an extent, and the percentage of light ions so high, that accurate values of T_i cannot be obtained

reliably. However up to the point where the uncertainty in T_i becomes large, the temperatures are clearly decreasing. This is true of both DMSP and C/NOFS.

[23] T_i measured on DMSP F16 in the BPDs is lower than values reported during other nighttime solar minimum conditions when T_e was approximately 600–700K over the Indian sector [*Bhuyan et al.*, 2002]. They are also lower than values predicted by the International Reference Ionosphere (IRI) model [*Gulyaeva and Titheridge*, 2006] run for these periods (June 2005 and June 2008) and approximate location (330°E longitude). These model values are approximately 1000K. We believe that the discrepancy between our results and past studies is due to the localized nature of BPDs, both in time and space. Variability in ion and electron densities and temperatures have been noted in previous studies [*Forbes et al.*, 2000; *Gulyaeva and Titheridge*, 2006] but no consistent study of density variations as functions of (1) solar cycle, (2) season, and (3) location has been undertaken until now.

5. Summary

[24] We have presented observations of BPDs and neutral density depletions which occur during June solstices, near the equator during solar minimum years. These observations were made from altitudes of 330 km to 840 km using several different detectors flown on a number of spacecraft. The appearance of simultaneous neutral density depletions in the equatorial region narrows the range of explanations to cooling or downwelling of the ionosphere and thermosphere during these times. This hypothesis is supported by direct measurements of plasma temperature, which also show minima in the equatorial region, well below the predicted values based on the IRI model or other observations. At present no mechanism has been proposed which accounts for the basic formation of BPDs or their climatology.

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